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Perspective Displays: A Review of
Human Factors Issues

Neelam Naikar

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Air Operations Division
Aeronautical and Maritime Research Laboratory

DSTO-TR-0630

ABSTRACT

Three-dimensional displays may be a more effective way of presenting spatial information to operators than conventional two-dimensional displays because all three dimensions of space may be represented in a spatial format. Of several three-dimensional computer graphics systems that are currently available, perspective displays may be the most viable option for implementation at the present time. Previous research shows that perspective displays support better performance than plan-view displays on navigation, spatial awareness, and integration tasks. However, several issues need to be carefully considered and understood before perspective displays may be safely operationalised. This report reviews these issues; monocular cues for depth perception, multiple cue interaction, frame of reference, perspective geometry, and geometric and symbolic enhancement features.

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Executive Summary

This report grew out of a requirement to evaluate the suitability of three-dimensional (3D) display technology for the Airborne Early Warning and Control (AEW&C) capability, a proposal which was developed under AIR 5077. The role of AEW&C will be to provide surveillance, air defence, and force coordination capabilities in defence of Australian sovereignty and national interests. Its operations will involve monitoring tactical situations, identifying and assessing potential threats, and initiating and monitoring responses to perceived threats. In order to perform these functions, it is essential that operators are able to rapidly compose an accurate mental model of the surrounding environment and tactical situation. During a mission, operators rely heavily on visual displays for building spatial awareness. Hence the importance of the effective display of visuo-spatial information to mission success cannot be overstated.

A major limitation of conventional plan-view displays is that operators have to integrate numerical information about altitude with spatial information about the horizontal dimensions of the visual scene and mentally reconstruct the 3D nature of the space in which they are operating. Three-dimensional displays, on the other hand, can depict all three dimensions of space in a spatial format thereby eliminating the requirement to integrate textual with spatial information. Current 3D computer graphics systems include perspective displays, stereoscopic displays, rotating displays, head-motion tracking displays, holographic displays, and multiplanar displays. On the basis of a comparison of display effectiveness, limitations, stage of development, and financial considerations it is proposed that perspective displays are the most viable option for implementation at the present time.

Previous research shows that perspective displays support better performance than plan-view displays on navigation, spatial awareness, and integration tasks. However, several issues need to be carefully considered and understood before perspective display technology may be safely operationalised. One issue is the monocular cues that will be implemented in the display; the number of cues to implement, which cues to represent, and the interaction of various combinations of cues. Research shows that monocular cues generally combine to produce an additive effect and that motion, occlusion, texture gradient, luminance, and perspective are dominant depth cues. The frame of reference that should be provided to the viewer is also an important consideration and there is some indication that an egocentric frame of reference may support better local guidance performance and ego-referenced awareness whereas an exocentric frame of reference may support better world-reference awareness.

An area which is perhaps the least well understood is the effect of perspective geometry on viewers' interpretations of the spatial relationships in a perspective image. Results from studies investigating the effect of geometric field of view angle on exocentric direction judgements and tracking performance are inconsistent and there is little information about how biases in interpreting a display vary with viewer-eyepoint position relative to the geometric field of view angle of the display. More clear cut are the findings regarding eyepoint elevation angle and azimuth viewing angle; for exocentric direction judgements and tracking tasks, optimal eyepoint elevation angles range from 15° to 60° and optimal azimuth viewing angles range from 0° to 45°.

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1. Introduction

The aim of this report is to highlight significant issues regarding the implementation of perspective displays. First the potential of three-dimensional (3D) displays to enhance spatial awareness is discussed and several 3D computer graphics systems are described. The remainder of the report then focuses on perspective displays; the empirical evidence for its effectiveness compared to conventional two-dimensional (2D) displays, the monocular cues that may be used to recreate the perception of depth, the effect of combining multiple cues, the issue of whether operators should be provided with an egocentric or exocentric frame of reference, and the effect of perspective geometry and visual enhancements on perceptual biases and distortions.

2. Spatial Awareness

Spatial awareness is an important component of situation awareness. Situation awareness has been defined as "the perception of elements in an environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future" (Endsley, 1995). In a flight environment, developing situation awareness involves an assessment of numerous factors both internal and external to the ownship. For instance, in order to identify the presence, magnitude, and possible intentions of a perceived threat, the operator must assess various aspects of aircraft behaviour such as range, heading, altitude, speed, attitude (climbing or descending) and location on earth. In order to evaluate alternative responses to the potential threat the operator must take into account the status of defensive assets, considering factors that may limit available options, such as equipment malfunction or damage, fuel availability, atmospheric conditions, and terrain. All of these evaluations are made within a constantly changing environment and under highly stressful situations in which timing is critical and errors may be catastrophic.

Spatial awareness refers to an operator's comprehension of the 3D geometry of the environment in which he/she is operating. Three-dimensional information contained in the environment includes the absolute distance of objects (distance from an observer to an object), the relative distance of objects (distance between one object and another object or the distance between different parts of a single object), and the true 3D shape of objects (Wickens, Todd & Seidler, 1989b). In a flight environment, this information is available to an operator directly from his forward field of view and other senses and from visual displays (Endsley, 1988). In some instances, for example at night or when objects are out of viewing range, the operator may have to rely solely on visual

displays for a spatial representation of the environment (Andre, Wickens, Moorman & Boschelli, 1991). Visual displays are therefore critical to operators' spatial awareness.

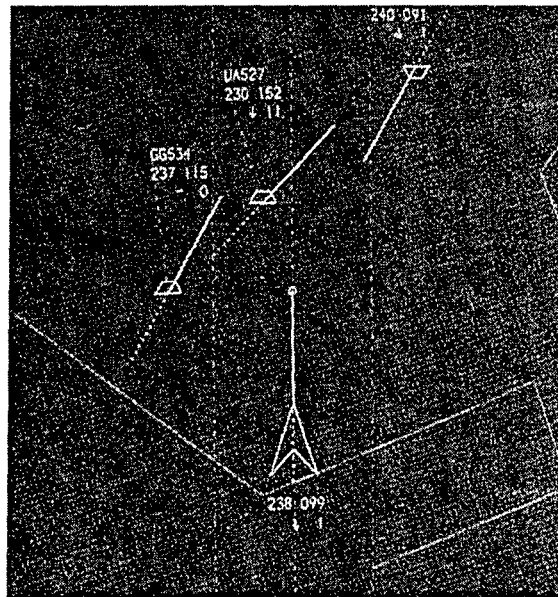


Figure 1: Plan-view display (from McGreevy and Ellis, 1991)

Currently, most operators rely on plan-view displays to develop mental models of the space in which they are operating. A major limitation of this type of display is that it can only represent information from two dimensions of space; the vertical dimension is typically encoded in a textual format (see Figure 1). To obtain information about the vertical dimension of a track in the environment, operators are required to "hook" the track and press a button to obtain textual readouts of altitude. To determine aircraft attitude, operators must monitor altitude readouts over time and observe changes. Operators are therefore forced to integrate textual with spatial information and mentally reconstruct the 3D nature of the visual scene. This process requires valuable cognitive resources and decision-making time (Haskell & Wickens, 1993).

These limitations of plan-view displays may be overcome by 3D display technology. Three-dimensional displays can depict all three dimensions of space in a completely spatial format thereby eliminating the requirement to integrate textual with spatial information (see Figure 2). All of this information is contained within a single display which reduces the need for mental integration of information from multiple sources (Woods, 1984). Three-dimensional displays also provide a more natural or ecological representation of the "real world" (Wickens et al., 1989b).

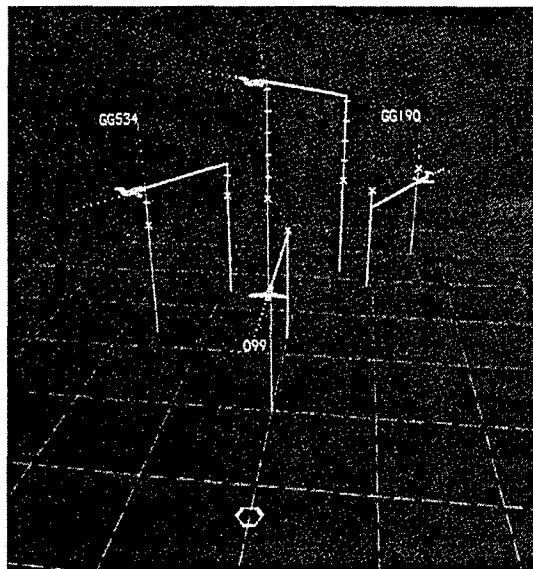


Figure 2: Perspective display

3. Three-dimensional Computer Graphics Systems

Three-dimensional computer graphics systems include perspective displays, stereoscopic displays, rotating displays, head-motion tracking displays, holographic displays, and multiplanar displays. In this section, particular emphasis is placed on perspective and stereoscopic displays.

3.1 Perspective Displays

Perspective displays utilise the cue of linear perspective to create a 3D projection of an object on a computer screen. This is achieved by having straight projection rays, which emanate from the centre of projection (or station point) of the object, pass through each point of the object and intersect the projection (picture) plane or computer screen. Figure 3 shows the relationship between a 3D stimulus and its perspective projection. A parallel projection is obtained when the centre of projection is at infinity and all the projection lines are parallel. A perspective projection is obtained when the centre of projection is at a finite distance. Perspective displays are popular because its 3D characteristics most closely match the features of the human visual system (Yeh & Silverstein, 1992). However, the representation of 3D information on a 2D surface can create perceptual biases and distortions (see section 8).

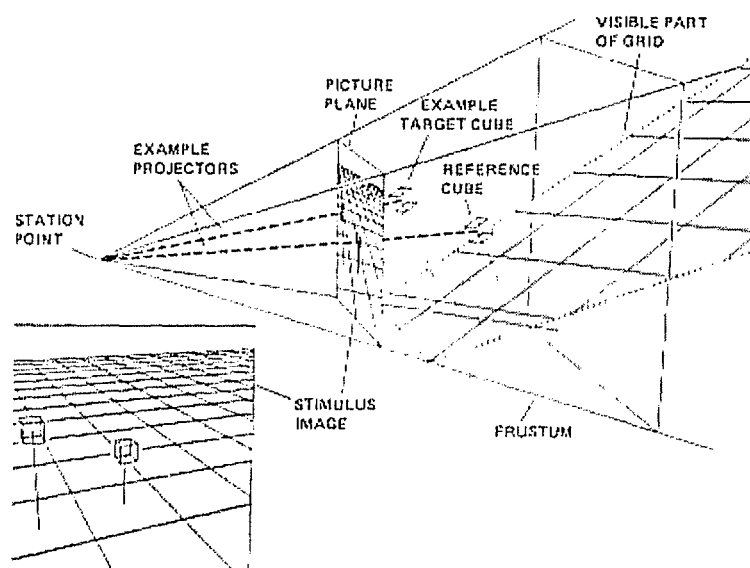


Figure 3: A perspective projection of a 3D stimulus (from McGreevy and Ellis, 1986)

3.2 Stereoscopic Displays

Stereoscopic displays utilise the cue of binocular disparity to create a perception of depth by presenting two slightly different views of the same visual scene to the left and right eyes. This is achieved by slightly changing the camera eyepoint of the visual scene for the two eyes causing each point in the scene to be rotated and translated a specific amount. The images presented to each eye can either be viewed simultaneously (time-parallel displays) or in alternation (time-multiplexed displays). In the case of time-parallel displays, the two disparate images are presented in different wavelengths of light and then different filters on each lens of a pair of glasses are used to present a different image to each eye. In time-multiplexed displays the two disparate images are presented at a rapid pace of alternation (usually around 30 Hz) and each lens of the glasses used for viewing is polarised to a different orientation to ensure that each image is viewed only by the appropriate eye. These displays are currently the most frequently used stereoscopic display technology. However, there are several limitations associated with these systems (Wickens et al., 1989b).

First there are physical constraints; the viewer must wear glasses that are synchronised to the display which requires a great amount of wiring. Second, alternating frame technologies produce a distorted image as the viewing perspective changes and 3D imaging is lost if the head is tilted. Third, the use of the polarisation technique eliminates much light energy from the visual scene so that images are less intense. Fourth, the use of raster displays means that the left and right eye images are generated on alternating raster lines; a feature which degrades the vertical resolution of the display.

Finally, current stereoscopic displays raise large cost barriers. While many of these limitations are being minimised or even eliminated with rapid developments in computer technology, some unresolvable problems remain: fatigue is caused by the imbalance of visual information provided to the two eyes, and approximately 10% of the population are unable to fuse stereoscopic images.

3.3 Rotating Displays

Rotating displays generate three-dimensionality by utilising a motion-based cue called the kinetic depth effect. The kinetic depth effect refers to the perception of depth that is obtained by viewing a 2D projection of an object undergoing 3D rotation around its vertical and horizontal axes. Expensive and sophisticated high-speed graphics software is required to enable the interactive rotation of complex images around a given axis and to produce the effect of continuous smooth motion (Sollenberger & Milgram, 1993). The visual effect of motion is not easily obtainable on a personal microcomputer because image update rates are slow.

3.4 Head-Motion Tracking Displays

Head-motion tracking displays utilise the cue of motion parallax for creating a perception of depth. Motion parallax is created by tracking the head movements of the observer and updating the viewpoint of the computer-generated image in real time. Objects that are closer to the observer are displaced by greater distances than are objects that are farther away. Objects at similar distances from the observer are displaced by approximately equal distances. Head-motion tracking displays have the advantage of providing the observer with several viewing perspectives of the visual scene. However, the requirement for rapid display updating which is tied directly to head movements is computationally very intensive.

3.5 Holographic Displays

Holographic displays create virtual 3D images by employing a technique of optical interference between images projected from two different light sources. Despite the fact that the images exist in 3D space, this technique may produce distortions in relative distance judgements (Wickens et al., 1989b). Another disadvantage is that there are technological difficulties associated with generating real-time holography that can be dynamically updated. This problem is exacerbated by the fact that holographic displays are limited in field of view so that images have to be continually updated in response to the observers' viewing angle.

3.6 Multiplanar Displays

Multiplanar displays (also known as volume visualisation displays) create a virtual volume within which a 3D image can be generated by employing a system of rotating or vibrating mirrors. The benefits of this system are its virtuality and that it allows multiple users to walk around and inspect the display. Its limitation is its unsuitability for creating solid objects, area shading, and filling. This technology is expensive and still in the early stages of development.

3.7 Perspective versus Stereoscopic Displays

Even though there have been great advancements in computing technology for immersive or virtual reality displays (head-motion tracking, holographic, multiplanar), substantial improvements in hardware and software are necessary before these displays can be applied successfully in a cost-effective manner (Durland & Mavor, 1995; Wilson, 1997). Immersive-display technology is still considered to be in the early stages of evolution and it is still a major challenge to generate immersive environments that appear convincingly real to users and that allow them to interact with the environment in real time (Durland & Mavor, 1997; Wilson, 1997). Furthermore there is limited research on the types of tasks that may be effectively performed by humans interacting with immersive displays and there is also some concern about the long-term physical and psychological effects of using this type of technology (Stanney, 1995). For these reasons, it was judged that perspective and stereoscopic displays are the most viable options for implementation at the present time.

Some researchers have compared the relative effectiveness of stereoscopic and perspective displays for various types of tasks; the major observations from this body of research are outlined here. First, although stereopsis is a compelling and powerful depth cue, it has been shown that it is only particularly useful if the display is static or changing slowly (Wickens et al., 1989b; Yeh and Silverstein, 1992). In a dynamic task with a rich visual environment, the addition of stereoscopic information does not improve performance over that of a similar display without stereopsis. Second, the advantage of stereopsis is not necessarily more profound than that offered by other salient cues such as motion parallax and occlusion (Wickens et al., 1989b). Third, stereoscopic displays only offer significant advantages over perspective displays when monoscopic cues used in the perspective display are degraded (Pepper, Smith & Cole, 1981; Yeh & Silverstein, 1992). Fourth, stereoscopic viewing does not show a significant advantage over monoscopic viewing when visual enhancements are incorporated into perspective displays (Kim, Ellis,

Tyler, Hannaford & Stark, 1987). Finally, it has been shown that performance is as accurate with perspective displays as with stereoscopic displays when the geometric parameters of the perspective display are appropriate (Kim et al., 1987). In light of these research findings and the limitations associated with stereoscopic displays (see section 3.2), it is proposed that perspective displays may be the more viable 3D display technology. The remainder of this report focuses on issues relevant to perspective displays.

4. Two-dimensional versus Perspective Displays

How effective are perspective displays? Research addressing this issue may be divided into two categories: studies that have compared perspective with 2D display performance and studies that have simply evaluated perspective display performance (Haskell & Wickens, 1993). The results of research from the latter category have shown that perspective displays can result in satisfactory, and even excellent, landing performance of different types of aircraft (Adams, 1982; Barfield, Rosenberg, Han & Furness, 1992; Grunwald, 1984; Grunwald & Merhav, 1978; Jensen, 1981; Martin & Way, 1987; Roscoe & Jensen, 1981; Scott, 1989; Setterholm, Mountford & Turner, 1982; Wickens, Haskell & Harte, 1989). Although contrary findings were obtained by Wempe and Palmer (1970), the display used in their experiment had only a minimal number of depth cues (Haskell & Wickens, 1993). Nevertheless, the findings from this category of research do not tell us whether perspective displays are more effective than 2D displays. Studies that examine this issue may be grouped according to the type of task that the displays were used to support: navigation, spatial awareness, and integration versus focussed-attention tasks.

4.1 Navigation

Wickens and Schattenmann (1968) evaluated pilot performance on a simulated flight-path tracking task using three different displays: a 3D display with motion and linear perspective cues, a 2D flight director display, and a standard instrument landing system (ILS). The perspective and 2D displays produced better tracking accuracy than the ILS instrument. The perspective display showed an advantage over the 2D display in the most difficult condition in which the pilots were required to land the aircraft in a cross wind. Otherwise, there was no difference in tracking performance between the two displays.

Grunwald, Robertson and Hatfield (1981) compared an enhanced 2D cockpit display with various perspective displays for landing performance. The perspective displays allowed pilots to maintain better flight-path tracking accuracy than the 2D display. Secondary task performance was also better with

the perspective displays indicating reduced workload. However, generalising from the results obtained in this study is difficult because only four pilots participated in the experiment.

4.2 Spatial Awareness

Ellis, McGreevy and Hitchcock (1984, 1987) examined how pilots' avoidance manoeuvres varied as a function of display type: plan-view versus perspective. Results from 10 airline pilots showed that the perspective display produced improved avoidance manoeuvring; pilots took less time to identify collision hazards and recommend a manoeuvre, fewer errors were made in selecting a manoeuvre, and pilots were more likely to achieve the required separation between ownship and the intruding aircraft. Pilots were twice as more likely to select a vertical manoeuvre with the perspective display probably due to the more natural presentation of vertical separation.

Bemis, Leeds and Winer (1988) compared a plan-view with a perspective display for the task of detecting an airborne threat and selecting the closest friendly aircraft to intercept the threat. The results from 21 naval operational personnel showed that fewer errors in detecting threats were made in the perspective display condition. The subjects were also more accurate and quicker at intercepting aircraft using the perspective display. Survey results showed that 19 of the 21 subjects preferred the perspective display.

Contrary to the above findings, Tham and Wickens (1993) obtained superior performance with the plan-view display in their experiment. Air traffic controllers, pilots and novices were required to make heading judgements, vector aircraft to specified locations, identify the highest aircraft, identify the fastest aircraft, and identify potential conflicts between aircraft. Except for identifying potential conflicts, where there was no difference between the two display formats, all of the judgements were better with the plan-view display. In a second experiment, air traffic controllers and pilots were tested in a more realistic traffic management task. The only difference between the two displays was that subjects were slower in detecting unexpected aircraft heading changes with the perspective display.

4.3 Integration versus Focussed Attention

Haskell and Wickens (1993) have suggested that tasks may be differentiated on the basis of whether they require integration or focussed attention. Integration tasks require judgement or control that depends on the integration of information across the horizontal, vertical and depth axes. One example of a task requiring integration is flight control whereby pilots must integrate the three dimensions of location and the rate of change along these

dimensions (eg heading, airspeed) (Rate & Wickens, 1993). Focussed-attention tasks require subjects to focus their attention on only a single or a pair of axes. An example of a task requiring focussed-attention is making precise readings along the vertical axis to determine the vertical separation of aircraft (Rate & Wickens, 1993). Haskell and Wickens (1993) have proposed that perspective displays, which integrate all three dimensions of space in a single format, will produce superior performance on integration tasks but that this advantage may be reduced or even eliminated for tasks requiring focussed attention.

Haskell and Wickens (1993) compared the effectiveness of a plan-view format (comprising of three orthogonal spatial views so that it was not placed at a disadvantage by the use of alphanumeric information) with a perspective display for performing integration and focussed-attention tasks. Twenty pilots were required to land a simulated aircraft several times using either one of the displays. The perspective display supported superior lateral and altitude flight-path tracking accuracy (integration task) whereas the 2D display supported better airspeed tracking accuracy (focussed-attention task). There was no difference in the latency and accuracy of integrated judgements (point and time of closest passage of an intruder aircraft) and focussed-attention judgements (relative altitude of and distance to intruder aircraft) between the two displays. However, the requirement to make integrated judgements interfered less with flight accuracy when using the perspective display whereas the reverse was observed for focussed-attention judgements.

4.4 Summary

Research has shown advantages for both navigation and spatial awareness performance with perspective displays. However, Haskell and Wickens (1993) have shown that plan-view displays may support better performance on focussed-attention tasks. This may explain why Tham and Wickens (1993) found that heading, altitude, and speed judgements were better with a plan-view display than a perspective display. Hence, for tasks that require focussed-attention it may be better to utilise a plan-view format that provides a spatial representation of altitude than a perspective display. On the other hand, perspective displays may be better for tasks that require integration over several dimensions. For a job that involves both integration and focussed-attention judgements it may be beneficial to provide the operator with the flexibility to switch between the two display formats.

5. Monocular Visual Cues for Depth Perception

One challenge facing the designer of a perspective display is appropriate implementation of monocular cues in the display so that it provides the user with an accurate sense of three-dimensionality. Issues that need to be considered include the number of monocular cues that should be selected and which cues to represent. Monocular cues that exist in the natural world include: (1) light (luminance and brightness effects, aerial perspective, shadows and highlights, colour, texture gradients), (2) occlusion or interposition, (3) object size (size-distance invariance, size by occlusion, familiar size), (4) height in the visual field, and (5) motion (motion perspective, object perception). As Wickens et al. (1989b) provide a comprehensive description of each of these cues, only a brief description is provided here.

5.1 Light

Luminance or brightness differences between two regions convey information about depth. Egusa (1977, 1983) has demonstrated that the amount of depth perceived to be separating two regions increases as the brightness differences between the two regions increases. It has also been shown that brighter parts of an object are perceived as closer together than dimmer parts of an object (Doshier, Sperling & Wurst, 1986). Another light cue, aerial perspective, occurs due to the desaturation and/or addition of an environment's ambient hue to a visual scene. Aerial perspective causes objects in the distance to be seen less clearly than objects that are closer to the observer.

Shadows and highlights also convey information about depth. An attached shadow (cast by and falling upon an object itself) shows the shape and characteristics of the object's surface and indicates whether a given area is extended or intended from the surrounding surface (Cavanagh, 1987). A cast shadow (falling off an object onto a background) provides information about the distance of the object as well as influencing the perception of the surface upon which the object casts its shadow (Rock, Wheeler, Shallo & Rotunda, 1982). A highlight, which is a "spot" of reflected light from a specular source, also provides a cue to depth by the direction of its movement on an object's surface. On a convex surface the highlight moves in the same direction as a moving light source or observer whereas on a concave surface the highlight moves in the opposite direction to the moving light or observer.

An object's perceived depth can also be influenced by hue and saturation. Egusa (1983) has shown that objects that are red in colour will be judged to be closest to the observer followed by green objects then blue objects. Also, the perceived distance separating two regions increases as the difference

in saturation levels between the two regions increases; the direction of perceived depth differs across hues (Egusa, 1983).

Finally, texture gradients provide information about the distances and slants of surfaces as well as the size of objects located on those surfaces. The texture of a surface refers to the spacing and size of the elementary features of which it is composed. Three types of texture gradients provide cues to depth: 1. perspective gradient (change in the x-axis width of a single element), 2. compression gradient (ratio of y/x axes measures of the element), and 3. density gradient (the number of elements per unit of visual angle).

5.2 Occlusion

Occlusion refers to the apparent interposition of objects relative to an observer's viewpoint. An occluded object is perceived as being more distant than the object that is obscuring it. This cue is enhanced with familiar objects (due to the assumption that the more distant object continues behind the occluding object) and with the presence of high spatial frequency information on the surface of the occluding object.

5.3 Object Size

Object size can convey information about depth in a number of ways. First, the size-distance invariance relationship implies that objects with the same visual angle are the same distance away, and that objects with a smaller visual angle are farther away than objects with a larger visual angle. Second, depth can also be estimated from the number of elementary texture units of a background surface that are occluded by an object. An object is perceived to be more distant the greater the number of texture elements it occludes. Third, as a familiar object maintains a constant perceived size regardless of the objective visual angle subtended by the object, the perceived distance of the object becomes a function of the visual angle of the object.

5.4 Height in the Visual Field

In a typical visual scene it is assumed that the foreground is lower than the horizon. Based on this assumption, an object which is higher in the visual field is perceived to lie farther away from an observer than an object that is lower in the visual field. However, this rule only holds for objects that are located below the horizon. Objects that are above the horizon appear more distant the lower they are in the visual field.

5.5 Motion

Cues to depth are also provided by the movement of an observer and/or the movement of an object. Motion perspective refers to the observation that when a person moves the images of the objects on which the person is fixating shift relative to each other. The greater the objective distance between the objects, the more the images of the objects shift relative to each other. Motion parallax is a unique case of motion perspective. When a moving observer is fixating on a particular spot, objects closer to the observer than the spot being fixated on will appear to move in the opposite direction to the movement of the observer. Objects that are farther away from the observer than the spot on which he is fixating will appear to move more slowly and in the same direction as the movement of the observer. Another motion cue is the kinetic depth effect which refers to the perception of a 3D object from its 2D projection on a screen as a result of rotation of the object. When the 3D object is rotated around the X or Y axis of the screen the perception of the 2D projection as a 3D object will emerge.

6. Multiple Cue Interaction

In a perspective display various combinations of monocular cues may be utilised to create a perception of depth. An important consideration is how the cues interact with each other to create a perspective image. According to the weighted additive model, depth perception is a weighted linear function of the number of depth cues available in a display; the greater the number of depth cues the greater the sensation of depth that is created (Bruno & Cutting, 1988). The cues may be of equal weights or some may be dominant over others. According to the multiplicative model, however, different depth cues interact with one another to produce either a subtractive (a cue's influence is diminished) or additive (a cue's influence is enhanced) effect (Wickens et al., 1989b). Therefore the contribution of a given cue depends on the number or kinds of cues already present in the display.

Two techniques have been used to study the relative strengths of different cues in conveying depth information. In cue trade-off studies, two or more cues which portray conflicting information about an object's location or orientation in depth are presented to an observer. The observer's perception of the location or orientation of the object is used to assess the relative dominance of the cues. In cue compellingness studies, two or more cues which provide congruent information about the depth of an object are presented to an observer and changes in the strength of the observer's depth sensation as different cues are added is examined. Cue trade-off and cue-compellingness studies are

reviewed by Wickens et al. (1989b) in detail. The major findings from this body of research are summarised here.

First, motion is a dominant cue. When combined with other cues, its effects are either additive, positive (motion enhances the value of the other cue), or negative (motion lessens the effect of the other cue). The effect of motion itself, however, is not reduced by other cues. Second, while there are few studies looking into the effects of occlusion or interposition on depth perception, the existing evidence indicates that it is a strong and dominant cue. Third, texture gradient, luminance, and perspective cues are less dominant but also effective cues for depth. Fourth, relative size and highlighting cues have been found to be relatively weak indicators of depth. Fifth, monocular cues generally combine to produce an additive effect, thereby providing support for the weighted additive model. Finally, cue dominance is task dependent; careful study of the interaction of various cues in the relevant context is necessary prior to operationalisation.

7. Frame of Reference

The frame of reference that is provided to a viewer is also an important consideration in perspective display design (Andre et al., 1991; Aretz, 1991; Barfield et al., 1992; Baty, Wempe & Huff, 1974; Ellis, Tyler, Kim McGreevy & Stark, 1985; Harwood & Wickens, 1991; Olmos, Liang & Wickens, 1997; Rate & Wickens, 1993; Wickens & Battiste, 1994; Wickens, Haskell & Harte, 1989; Wickens, Liang, Prevett & Olmos, 1994, 1996; Wickens & Prevett, 1995). Should the viewer be provided with an egocentric or exocentric view of the scene? In an egocentric or pilot's eye display, the symbol representing ownship remains stationary while the flight environment moves around it. In an exocentric or god's eye display, the symbol representing ownship moves while the flight environment remains stationary. It has been proposed that the frame of reference that is implemented should be compatible with the viewer's mental model of his/her movement through the environment (Artez, 1991; Barfield, Rosenberg & Furness, 1995b; Wickens et al., 1989a). Several studies have shown that the viewer's mental model of his/her movement through the environment may depend on whether the viewer is performing local guidance or global awareness functions.

7.1 Local Guidance versus Global Awareness

The relative effectiveness of an egocentric and exocentric frame of reference for performing local guidance and global awareness tasks has mainly been examined in the context of airspace navigation. Local guidance refers to

the task of remaining on a nominated navigation path through either 2D or 3D space (Wickens & Prevett, 1995). As control inputs to minimise deviations from the flight path (eg descending, turning) are made with respect to an egocentric frame of reference (pilot's forward field of view), local guidance would best be supported with an egocentric display (Olmos et al., 1997). Global awareness refers to the knowledge of where objects are located in space, both in terms of one's momentary position and orientation (ego-referenced) and in terms of a stabilised coordinate system (world-referenced) (Wickens & Prevett, 1995). As the information needed by navigators to create a mental map of the environment requires a frame of reference which is consistent in depicting world features, global awareness would best be supported with an exocentric display (Olmos et al., 1997).

Several studies have assessed the reliability of these predictions. The results of experiments conducted by Barfield and his colleagues have been consistent with the predictions (Barfield et al., 1992; Barfield et al., 1995b). In one study, 13 flight-naïve subjects were required to fly a simulated F-16 and lock onto and intercept a series of sequentially appearing targets (local guidance) (Barfield et al., 1995b). The egocentric frame of reference produced smaller horizontal and vertical root mean square errors and faster target lock-on and target acquisition times. The subjects were also required to construct, from memory, a spatial model of the targets they had encountered during the flying task (global awareness). The exocentric frame of reference supported better performance on the spatial reconstruction task. Similar findings were obtained by Barfield et al. (1992).

However, the results of studies conducted by Wickens and his colleagues have not been so clear cut. Wickens et al. (1989a) measured flight-path performance (local guidance) and situation awareness (global awareness) for pilots flying approach paths to North American airports using either an egocentric or exocentric perspective display. The data showed that flight-path performance was superior with the egocentric frame of reference. However, there was no difference in situation awareness between the egocentric and exocentric frame of reference.

Andre et al. (1991) compared an exocentric perspective display with both an egocentric and an exocentric plan-view display. Eleven flight-naïve subjects were instructed to fly a simulated aircraft to as many of eight waypoints positioned in 3D space as possible (local guidance). On random occasions the display would blank and subjects would be thrown into an unpredictable bank and pitch angle. Upon reappearance of the display, subjects were required to reorient to the correct waypoint as quickly as possible (global awareness). The greatest number of destinations reached as well as the quickest reorienting times were obtained with the exocentric plan-view display. Here, the exocentric frame of reference supported better local guidance and global awareness.

Rate and Wickens (1993) employed a completely crossed design in which a 2D display and a perspective display were represented in either an egocentric or exocentric frame of reference. Thirty-five novice subjects were instructed to minimise flight-path deviations as they flew simulated landing approaches (local guidance). In addition, they were asked questions about the position and height of the nearest terrain hazard at various intervals during the experiment (global awareness). Lateral flight-path control was better with an egocentric than an exocentric frame of reference. Vertical flight-path control was not affected by frame of reference which is to be expected as vertical control is not reversed in compatibility by changes in frame of reference. Response error and latency measures of situation awareness showed no main effect of frame of reference.

More recent studies by Wickens and his colleagues have measured two separate components of situation awareness (ego-referenced and world-referenced awareness) and obtained more consistent findings with respect to the effect of frame of reference on global awareness. In a study by Wickens et al. (1994), in which 24 pilots were required to fly eight simulated curved-approach landings, the egocentric frame of reference supported faster and more accurate responses to ego-referenced questions (subjects were required to judge location and altitude of particular terrain features in relation to themselves, for example, relative heading from the aircraft). The exocentric frame of reference supported quicker and more accurate responses to world-referenced questions (subjects had to judge the relationship between two terrain objects, for example, absolute compass bearing). As expected, the egocentric frame of reference minimised lateral and vertical tracking error. These findings were replicated by Wickens et al. (1996).

In an experiment by Olmos et al. (1997), 30 aviation personnel with extensive flight experience were required to fly a simulated visual approach to landing. The results showed better lateral and vertical tracking with an egocentric frame of reference. This view also supported faster and more accurate ego-referenced judgements. There was no effect of frame of reference on world-referenced judgements. The exocentric view supported only marginally better map-reconstruction performance than the egocentric view. It was thought that the costs of mental rotation associated with using the exocentric frame of reference to maintain flight-path performance may have allowed fewer resources to be allocated to learning the spatial layout of the terrain.

Wickens and Prevett (1995) carried out a more detailed assessment of the effect of frame of reference on local guidance and global awareness. Rather than using purely egocentric and exocentric views, they measured pilot navigation and situation awareness in a 2D display (exocentric) and in a set of four 3D displays that varied in degree of egocentricity of viewpoint location. All

viewpoints were tethered to the aircraft with varying lengths: 0m (egocentric), 3000m (close exocentric), 7500m (mid exocentric), and 21000m (far exocentric). The results showed that the 3D egocentric view supported better lateral and vertical tracking as well as faster responses to situation awareness questions than the exocentric views (2D and 3D). However, the exocentric views (2D and 3D) supported more accurate responses to situation awareness questions than the 3D egocentric view. Comparisons of the three 3D exocentric views showed that the mid-exocentric view supported better overall tracking and more accurate responses to world-referenced situation awareness measures than the close view or the far view.

7.2 Flight Experience

Operators' flight experience may also be an important consideration in selecting an egocentric or exocentric frame of reference for a display. After reviewing the literature, Wickens et al. (1989b) concluded that subjects with no flying experience prefer an exocentric frame of reference whereas experienced pilots favour an egocentric frame of reference.

7.3 Summary

The findings from this area of research provide some indication that an egocentric frame of reference may support better local guidance performance and ego-referenced awareness whereas an exocentric frame of reference may support better world-referenced awareness. If the display under design is to be used to support a single function or two compatible functions (eg local guidance and ego-referenced awareness) concurrently, then the decision as to which frame of reference to implement is an easy one. However, if two incompatible functions (eg local guidance and world-referenced awareness) are to be performed concurrently the decision becomes more difficult. The implementation of separate displays with different frames of reference may create a high mental workload as a result of the requirement for cognitive integration (Olmos et al., 1997). Another option may be a single display that supports local guidance/ego-referenced awareness and world-referenced awareness. There is some evidence that a 3D display with a mid-exocentric frame of reference may meet this criterion (Wickens & Prevett, 1995).

8. Geometric Parameters in Perspective Displays

The geometric parameters of a perspective display define the 3D nature of a perspective projection on a 2D screen. These parameters include the geometric field of view (GFOV) angle and, when the perspective display

presents an exocentric frame of reference, the eyepoint elevation angle (EPEA) and the azimuth viewing angle (AVA). As will be shown in the following sections, the geometry that is used to define a perspective projection may influence the accuracy with which observers recreate spatial relationships from the display (McGreevy & Ellis, 1986; McGreevy, Ratzlaff & Ellis, 1986).

8.1 Geometric Field of View

In a perspective projection, projectors from the centre of projection of an object to the projection plane define edge clipping planes on the left, right, top, and bottom sides of the projection (see Figure 4). The GFOV angle refers to the visual angle that subtends the centre of projection to the edge clipping planes. The horizontal GFOV angle is the horizontal angle from the centre of projection to the left and right edge clipping planes whereas the vertical GFOV angle is the vertical angle from the centre of projection to the top and bottom edge clipping planes.

The GFOV angle can be either veridical, telescopic or wide angle (Rate and Wickens, 1993). A veridical GFOV angle is one in which the landmarks on the display are positioned where they would be as seen by a pilot looking out of the cockpit at the terrain. A telescopic GFOV angle provides a narrower view which results in a magnification of the scene whereas a wide-angle GFOV provides a wider view which results in minification of the scene. The GFOV angle is manipulated by moving the computer graphics eyepoint towards or away from the viewport. Figure 5 shows that a GFOV angle of 30° will produce a more telephoto type of image whereas a GFOV angle of 85° will produce a more wide-angle type of image. Decreasing the GFOV angle increases the size of the image displayed on the picture plane (magnification effect) whereas increasing the GFOV angle decreases the size of the image displayed on the picture plane (minification effect).

A non-veridical GFOV angle can cause perceptual biases and distortions in viewers' interpretations of a perspective image due to the fact that the viewer's eye is not at the centre of projection of the display (Ellis et al., 1985; McGreevy & Ellis, 1986). Nevertheless non-veridical GFOV angles are sometimes employed in displays to reduce or eliminate certain perceptual biases. For example a narrow GFOV angle, which produces scene magnification, compensates for the tendency of pilots to perceptually minify a visual scene (Roscoe, Corl & Jensen, 1981). The necessity for using non-veridical GFOV angles makes it important to determine its effects on viewers' accuracy at recreating spatial relationships from a perspective display. Studies in this area

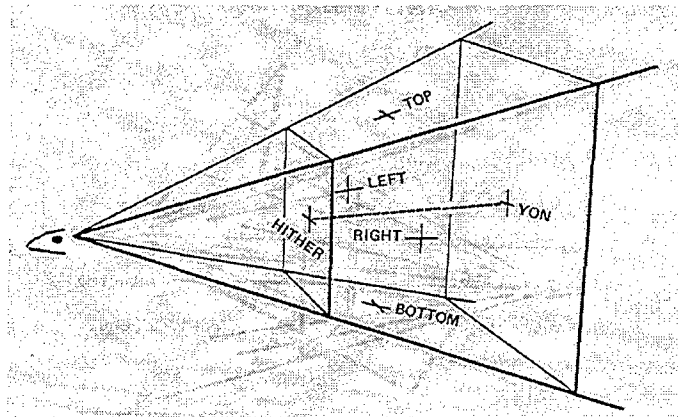


Figure 4: Projectors from the centre of projection to the projection plane define edge clipping planes on the left, right, top, and bottom sides of the projection (from McGreevy and Ellis, 1991).

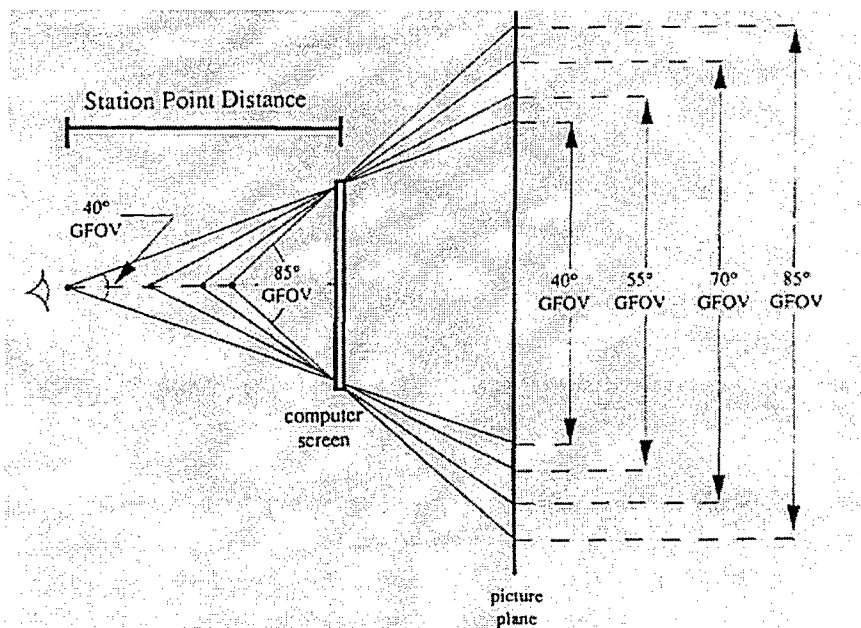


Figure 5: Illustration of four different GFOV angles (from Barfield, Hendrix and Bjorneseth, 1995a)

have been conducted in the context of exocentric direction judgements and manual tracking tasks (Barfield & Kim, 1991; Barfield et al., 1995a; Barfield, Lim & Rosenberg, 1990; Barfield et al., 1995b; Ellis et al., 1985; Ellis, Smith & McGreevy, 1987; Ellis, Tharp, Grunwald & Smith, 1991; Hendrix & Barfield, 1994; Kim et al., 1987; McGreevy & Ellis, 1986).

8.1.1 Exocentric Direction Judgements

Exocentric direction judgements, for example judgements of the azimuth and elevation angles separating two objects, are common to many spatial tasks such as determining the vertical and lateral separation between aircraft, navigating in a real or virtual environment, and map reading (Hendrix & Barfield, 1994). In a study by McGreevy and Ellis (1986), six pilots and two non pilots judged the azimuth and elevation angles of a target cube relative to a reference cube in 640 static perspective scenes. The effect of 30°, 60°, 90°, and 120° GFOV angles (which correspond to distances of 35.6 cm, 16.5 cm, 9.7 cm, and 5.6 cm from the screen) on performance was tested. The subjects' eye position was approximately 61 cm from the screen. The results showed significant effects of GFOV angle on elevation and azimuth judgements; the size of the effects were shown to be a function of the direction of target azimuth and elevation (also see McGreevy et al., 1986). Overall, a 90° GFOV angle produced the best elevation judgements whereas a 60° GFOV angle produced the best azimuth judgements.

Barfield et al. (1990) conducted a similar study in which 14 university students were required to judge the elevation and azimuth angles separating a reference cube from a target cube in a static perspective display. The GFOV angles tested were 30°, 45°, 60°, and 75°. The subjects were seated 40 cm in front of the screen. The results showed significant effects of GFOV angle on elevation and azimuth judgements. Azimuth judgement errors were greater at the 30° and 60° GFOV angles than at the 45° and 75° GFOV angles. Elevation judgement errors were greater at the 30° and 75° GFOV angles than at the 45° and 60° GFOV angles. Overall the 45° and 60° GFOV angles resulted in the best azimuth and elevation judgements, probably because they most closely approximated the actual field of view at the subjects' eye thereby resulting in the least distortion of the scene from the viewers' eyepoint.

Finally, Barfield et al. (1995a) tested the effect of four GFOV angles (40°, 55°, 70°, and 85°) on judgements of azimuth and elevation angles separating a target cube from a reference cube. The average viewing distance of the subjects from the computer screen was 50 cm which corresponds to a GFOV angle of 31.3°. The results from 12 subjects showed that GFOV angle did not affect judgements of elevation. However, there was a significant effect of the GFOV angle on azimuth judgements; the 40° GFOV angle produced the largest

azimuth error. There was no difference between the 55°, 70°, and 85° GFOV angles on azimuth judgements.

8.1.2 Tracking

In a study by Ellis et al. (1985), subjects controlled 2 two-axis joysticks to track the perspective projection of a cursor moving irregularly in three dimensions on a computer screen. The centre of projection of the display was set at either 2.5 cm, 20 cm, 40 cm, 80 cm, or 160 cm which corresponds to changes in GFOV angle ranging from 3° to 119°. The subjects viewed the display monocularly and their eyepoint was located 80 cm from the computer screen. The results showed a significant effect of the GFOV angle on normalised root mean square tracking error; only GFOV angles greater than 100° had a detrimental effect on tracking performance.

Kim et al. (1987) examined the effect of five GFOV angles (8°, 12°, 24°, 48°, 64°) on three-axis manual tracking performance. Contrary to the findings of the previous study (Ellis et al., 1985), the results from two adult male subjects showed that tracking performance deteriorated as the GFOV angle increased from 8° to 64°. Similar findings were obtained in another study examining the effect of GFOV angle on performance in a three-axis pick-and-place task (Kim, Tendrick & Stark, 1991). Neither of the two latter studies report the distance of the viewers' eyepoint from the display screen; it may be possible that the discrepancy in the findings between these studies and the earlier one (Ellis et al., 1985) are due to differences in viewer-eyepoint position.

Finally, Barfield et al. (1995b) examined the effect of three GFOV angles (30°, 60°, 90°) on interactive flight-path performance and a post-test reconstruction of the spatial layout of the flight environment. Thirteen flight-naïve subjects were required to fly a simulated F-16 over a computer-generated terrain and lock onto and intercept a series of targets. The results showed a significant main effect of GFOV angle for the three dependent measures of interactive flight-path performance (root mean square flight-path error, target lock-on time, and target acquisition time). Root mean square flight-path error was greatest with the 60° GFOV angle, with no significant difference between the 30° and 90° GFOV angles. Target lock-on time and target acquisition time were fastest with the 30° GFOV angle followed by the 90° and the 60° GFOV angles. There was no significant effect of GFOV angle on performance on the spatial reconstruction test (overall, horizontal, and vertical distance offset from actual target location to reconstructed location).

8.1.3 Summary

The inconsistency in the findings regarding the effect of GFOV angle on performance are probably largely due to the differences in the viewer-eyepoint position employed in the studies. No general recommendations for optimal GFOV angle can be provided from this work except to say that biases in judging the azimuth and elevation angles separating a target cube from a reference cube and detriment in tracking performance will arise when the viewer eyepoint is not positioned at the GFOV angle. Clearly, more research is needed to investigate how performance varies with changes in viewer-eyepoint position relative to the GFOV angle of the display.

8.2 Eyepoint Elevation Angle

The eyepoint elevation angle (EPEA) is the elevation of the centre of projection of the display with reference to the ground plane (see Figure 6). Changes in the EPEA of a perspective projection affects the amount of vertical and depth information contained in the image. As the EPEA increases from 0° to 90° (top-down viewing), the vertical compression of the visual scene increases so that less information about the y dimension of the display is provided to the viewer. As the EPEA decreases from 0° to 90° , the depth compression of the visual scene increases so that less information about the z dimension of the display is provided to the viewer.

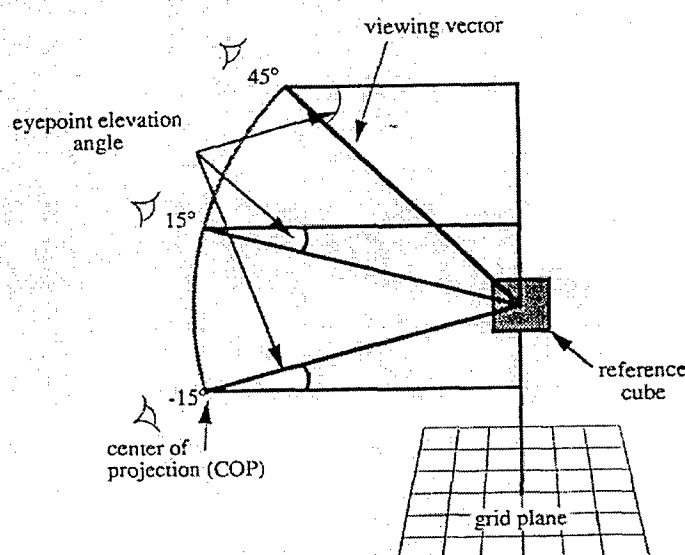


Figure 6: Illustration of three EPEAs (from Barfield et al., 1995a)

In selecting the EPEA of a perspective display one must be aware of the effects of depth and vertical compression on performance. Several studies have examined how changes in EPEA affect exocentric direction judgements and tracking performance (Barfield et al., 1995a, 1995b; Barfield, Rosenberg & Kraft, 1990; Hendrix & Barfield, 1994; Kim et al., 1987; Kim et al., 1991; Yeh & Silverstein, 1992).

8.2.1 Exocentric Direction Judgements

Yeh and Silverstein (1992) examined the effect of EPEA on judgements of the relative depth and altitude separating two target symbols on a perspective display. Twelve subjects were asked to determine which of two objects was closer along the z axis (depth judgements) and which of two objects was higher above the ground plane (altitude judgements). The results showed a significant effect of EPEA on type of judgement; depth judgements were faster at the 45° EPEA than at the 15° EPEA whereas altitude judgements were faster at the 15° EPEA than at the 45° EPEA. These results are consistent with the effects of depth compression at low elevations and vertical compression at high elevations.

Hendrix and Barfield (1994) examined the effect of EPEA on judgements of the azimuth and elevation angles separating a target cube from a reference cube. The effects of both positive and negative eyepoint elevation angles (EPEAs) were tested: -15°, 15°, 45°, and 75°. Results from 12 subjects showed a highly significant effect of EPEA on both azimuth and elevation judgements. Azimuth judgement error at the -15° EPEA was significantly larger than at the other three elevations. Elevation judgement error was significantly larger at the 75° EPEA than at the -15°, 15°, and 45° EPEAs. Overall, EPEAs ranging from 15° to 45° produced the best azimuth and elevation judgements.

Barfield et al. (1995a) examined the effect of three EPEAs (-15°, 15°, 45°) on judgements of the elevation and azimuth angle separating a target cube from a reference cube. The results from 12 subjects showed a significant effect of EPEA on both elevation and azimuth judgements. Elevation judgement error was larger with the -15° and 45° EPEAs compared to the 15° EPEA. Azimuth judgement error was larger at the -15° EPEA than at the 15° and 45° EPEAs. The best overall performance was produced by the 15° EPEA.

8.2.2 Tracking

Ellis et al. (1985) examined the effect of several EPEAs (0°, 15°, 30°, 45°, 60°, 75°, 90°) on subjects' performance in tracking the irregular movement of a cursor in three dimensions. The results showed that an EPEA of 45° produced the best tracking performance. Performance was worst at extreme elevation

angles (0° , 90°), which reflects that at the 0° elevation the subject loses information about the depth dimension whereas at the 90° elevation the subject loses information about the vertical dimension. Indeed, the results showed that the 0° EPEA produced poor z axis tracking whereas the 90° EPEA produced poor y axis tracking.

Kim et al. (1987) investigated how changes in EPEA (0° , -15° , -30° , -45° , -60° , -75° , and -90°) affect performance on a three-axis manual tracking task. The results from two adult male subjects were essentially the same as that obtained in the previous study (Ellis et al., 1985). That is, root mean square error increased as the elevation approached extreme angles (0° , 90°). The root mean square error was at a minimum at the -45° EPEA; at this elevation tracking performance was approximately equal along all three of the individual axes.

Barfield et al. (1995b), examined the effect of EPEA (30° , 60°) on tracking and post-test spatial reconstruction performance. Thirteen subjects were required to fly a simulated airplane through a computer-generated environment and lock onto and intercept a series of targets. The results showed that on the tracking task subjects' flight-path performance, target lock-on times, and target acquisition times were better at the 60° than at the 30° EPEA. Similarly, on the spatial reconstruction task (overall, horizontal, and vertical distance offset from actual target location to reconstructed target location in the visual scene), subjects performed better at the 60° than at the 30° EPEA.

8.2.3 Summary

Several conclusions may be made from studies examining the effect of EPEA on exocentric direction judgements and tracking performance. First, EPEAs approaching extreme angles of 0° and 90° have a detrimental effect on performance due to compression along the depth and altitude axes, respectively. Second, optimal performance may be obtained at an EPEA of 45° presumably because it accommodates judgements along both the depth and altitude axes. Third, EPEAs ranging from 15° to 60° can also produce good performance. Within this range, lower elevations foster better altitude judgements whereas higher elevations foster better depth judgements. The selection of the EPEA of a perspective display should be based on the relative importance of depth and altitude judgements to the viewer.

8.3 Azimuth Viewing Angle

The azimuth viewing angle (AVA) is the angle from which an object is viewed relative to a 0° (straight ahead) viewing orientation. Whereas changes in EPEA are achieved by rotation about the x axis of a visual scene, changes in

AVA are achieved by rotation about the y axis. Figure 7 shows a grid plane with a 45° AVA.

Two studies have examined how AVA affects tracking performance (Ellis et al., 1985; Kim et al., 1987). In the Ellis et al. (1985) study, the AVA was varied in 45° increments and two subjects were required to track an object moving in three dimensions. The 0° AVA produced the best tracking performance. The worst tracking performance occurred at azimuth viewing angles (AVAs) slightly over 90°. Accurate identification of the worst case was not possible because of the 45° increments in AVA. Therefore a second experiment was conducted in which the effect of 18 different AVAs, ranging from 0° to 180°, was tested. From 0° to 75°, the angles were varied in 7.5° increments after which the angles were varied in 15° increments. Again, tracking was best at an AVA of 0°. Tracking began to deteriorate at angles exceeding 50°. The worst performance occurred at the 135° AVA.

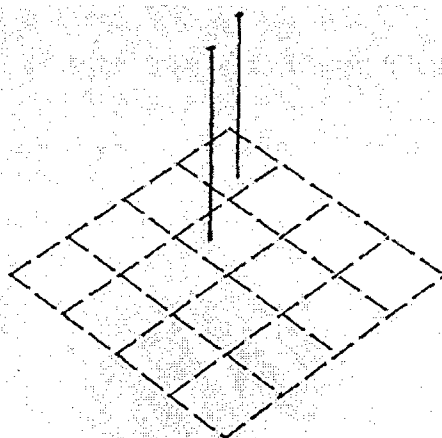


Figure 7: A grid plane with a 45° AVA relative to a "straight ahead" orientation (from Kim et al., 1987)

Kim et al. (1987) used a three-axis manual tracking task to examine the effect of AVA on performance. The AVAs used in the experiment were -135°, -90°, -45°, 0°, 45°, 90°, 135°, 180°. The results from two male subjects showed that tracking performance deteriorated markedly as AVA exceeded the range of -45° to +45°. The worst performance was obtained at the -90° and +90° AVAs.

Two conclusions regarding the effect of AVA on tracking performance may be drawn from these studies. First, best tracking performance occurs at an AVA of 0°; tracking is probably more difficult at AVAs other than 0° because of the rotation of the display frame relative to the viewer (Kim et al., 1987). Second, tracking performance starts to deteriorate at AVAs outside the range of -45° to +45°. Presumably, it becomes more difficult for the subject to compensate for the excessive rotation of the display frame at these angles (Kim et al., 1987).

8.4 Interaction of Geometric Parameters

In the preceding sections, the individual effects of three important perspective parameters (GFOV, EPEA, and AVA) on performance were considered. In a perspective display these parameters interact to produce a particular perspective image. Therefore, the effect of the combination of these parameters on performance must also be considered. Two studies, which were discussed earlier, have examined the effect of the interaction between GFOV and EPEA on performance. One of the studies involved an exocentric judgement task whereas the other study involved a tracking task.

Barfield et al. (1995a) examined the effect of varying the GFOV angle and EPEA on judgements of the azimuth and elevation angles separating a target cube from a reference cube. The GFOV angles in the study were 40°, 55°, 70°, and 85° and the EPEAs were -15°, 15°, and 45°. The results from 12 subjects indicated a significant effect of GFOV angle and EPEA on elevation judgements; the 40° GFOV angle and the -15° EPEA produced the largest error whereas the 40° GFOV angle and the 45° EPEA produced the smallest error. The errors doubled when the 45° EPEA was combined with either the 70° or 85° GFOV angle. In contrast, at the -15° EPEA, elevation errors decreased as the GFOV angle increased. There was also a significant effect of GFOV angle and EPEA on azimuth judgements. Again, the 40° GFOV angle and the -15° EPEA produced the largest azimuth judgement error. Azimuth errors decreased as the -15° EPEA was combined with larger GFOV angles. The 55° GFOV angle and the 15° EPEA produced the smallest elevation judgement errors. Overall, these results indicate that when a negative EPEA (-15°) is used to view the scene, larger GFOV angles (70°, 85°) which have the effect of minifying the scene should be used. However, when positive EPEAs (15°, 45°) are used to view the scene, smaller GFOV angles which have the effect of magnifying the scene should be used. Note, that a larger GFOV angle produces a more top-down view of the scene.

Barfield et al. (1995b) examined the effect of GFOV angle and EPEA on interactive flight-path performance and a post-test spatial reconstruction task. Subjects' task was to fly a simulated airplane through a computer-generated environment. The GFOV angles in the experiment were 30°, 60°, and 90° and the EPEAs were 30° and 60°. The results showed a significant effect of GFOV angle and EPEA on flight-path performance; the 60° EPEA and the 30° GFOV produced the best performance. These results show that a more top-down view of the scene combined with a GFOV angle that results in a greater amount of scene magnification enhances spatial awareness. It should also be noted that the 90° GFOV angle, which results in scene minification, produced the same level of performance at both the 30° and 60° EPEAs. This result suggests that larger

GFOV angles may decrease the effect of depth compression on performance that results from reducing the EPEA. There was no significant interaction between GFOV angle and EPEA on target lock-on time. However, GFOV angle and EPEA had a significant effect on target acquisition times; a 90° GFOV produced similar levels of performance for both EPEAs whereas at the 30° and 60° GFOV angles the 60° EPEA produced better performance than the 30° EPEA. This result suggests that when the scene is magnified, a higher EPEA will result in better spatial awareness of the flight scene. The interaction between GFOV and EPEA was not significant for the spatial reconstruction task.

The two studies show that the interaction between GFOV angle and EPEA can significantly affect performance on exocentric direction judgements and tracking tasks. The combination of geometric parameters used to produce a perspective image is therefore an important consideration. A suggestion has been made that giving the viewer flexibility to manipulate the GFOV angle, EPEA and AVA of the display may minimise the negative effects on performance that is caused by using fixed combinations of perspective geometry parameters (Barfield et al., 1995a). Display flexibility would also give viewers control over selecting the "best" view of the scene which may depend on the task to be performed. Criticisms of this technique are that it may foster a lack of consistency in the display (Wickens, 1990), that the viewer may get "lost" in the scene, and that the viewer may get distracted by changing the parameters of the display and neglect the task at hand. Solutions to these problems may be to restrict the flexibility given to the viewer, either by limiting the range of the GFOV angle and the EPEA that the viewer may interactively manipulate, or by providing a suitable number of optimal views of the scene which the viewer may select. The results of an unpublished study (Barfield & Hendrix, 1994; cited in Barfield et al., 1995b) have shown that judgements of elevation are more accurate when subjects are allowed to manipulate the EPEA than when a static EPEA is used. More research of this kind is necessary.

9. Visual Enhancements

The previous section showed how the interpretation of spatial relationships from a perspective display is subject to various perceptual biases and distortions. Several geometric scaling and symbolic enhancement techniques may be utilised to improve the interpretability of perspective displays.

9.1 Geometric Scaling

One geometric scaling technique that may be applied to perspective displays is that of magnification (Wickens et al., 1989b). Repeated observations have been made that objects on a visual display are seen as being smaller or closer together than they really are (Meehan, 1992; Meehan & Triggs, 1988; Roscoe et al., 1981). As a result, objects are perceived as being farther away from the observer than they really are. Roscoe et al. (1981) have proposed that a display magnification of approximately 1.3 is necessary to compensate for this bias. Meehan and Triggs (1988), on the other hand, have shown that the degree of magnification may depend on the amount of depth information contained in the display; smaller magnification effects are required for scenes containing more depth information. In addition, Meehan (1992) has reported that the minification bias may be naturally reduced as subjects gain experience with the task.

Another geometric scaling technique that has been applied to perspective displays is the amplification of the vertical dimension of the display relative to the horizontal dimension (McGreevy & Ellis, 1991). The horizontal and vertical dimensions of an aviation display are usually asymmetrical. For example, a typical separation is 1000 feet on the vertical dimension and 3 nautical miles on the horizontal dimension. In this case, the vertical dimension of the display may need to be scaled up by a factor of 18 in order to obtain a visual representation of the vertical separation (McGreevy & Ellis, 1991).

Finally, the technique of nonlinear scaling of object size with respect to distance may also be implemented in perspective displays (Wickens et al., 1989b). As a result of the size-distance invariance relationship, images of objects that are very far away will appear as very small on the display. Nonlinear scaling of object size with distance ensures that displayed objects do not become unperceivable if they are at extreme distances.

9.2 Symbolic Enhancements

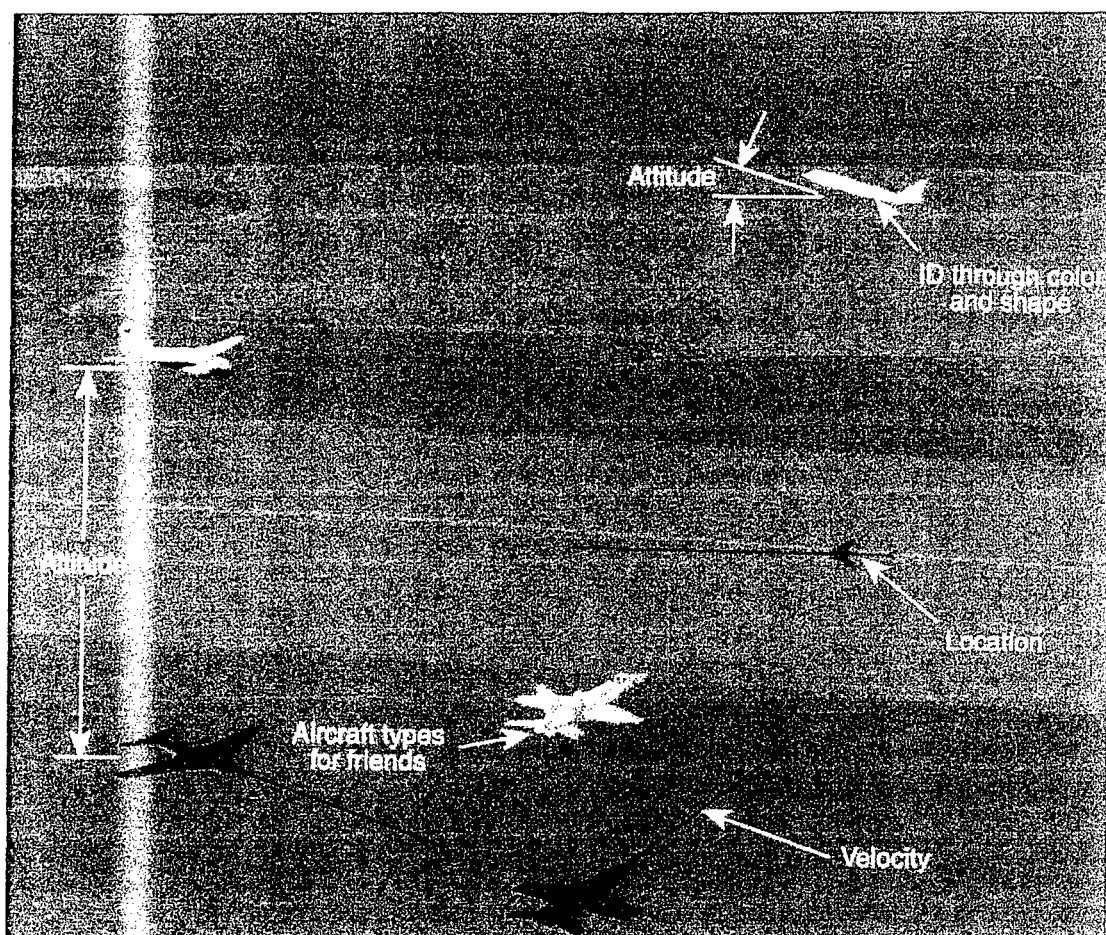


Figure 8: Perspective display developed by Applied Physics Laboratory, Johns Hopkins University (Dennehy et al., 1994)

McGreevy and Ellis (1985, 1991) have developed a perspective display for air traffic control that contains several symbolic enhancements which enhanced the effectiveness of the display in conveying spatial information (see Figure 2). The addition of a grid surface or ground plane to the display produced a marked improvement in the perception of depth. The regular lines of the grid also served as an indicator of the horizontal distance between objects in the display. A line which connected each aircraft to its true position on the ground plane made the relationship between each aircraft and the grid considerably more clear. The location of an "X" on the lines provided information about the vertical position of each aircraft with respect to ownship. Tick marks on the lines at 1000 foot intervals provided a measure of relative vertical separation.

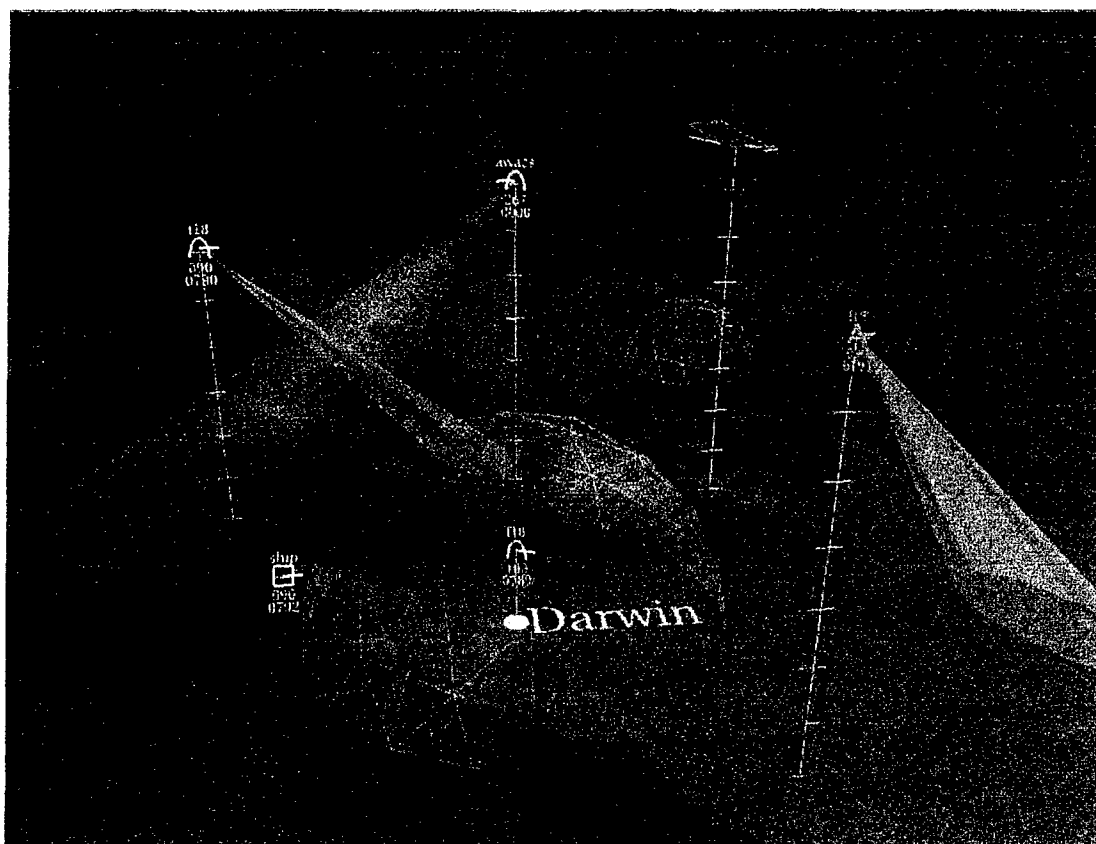


Figure 9: Perspective Display developed by Mission Systems Research Centre, Defence Science and Technology Organisation

Several symbolic enhancements were also utilised in a perspective display that was developed for the US Navy by the Applied Physics Laboratory at Johns Hopkins University (see Figure 8) (Dennehy, Nesbit & Sumey, 1994). In the display, the ground plane (earth) is shown as a sphere, the oceans are blue in colour, and the land masses are green. Transparent strips on the earth's surface depict commercial airline routes. Realistic 3D representations of air and surface craft indicate position and heading, and the shape and colour of the symbols denote tactical identification. The symbols are drawn with a pitch to indicate whether an aircraft is ascending, descending, or level in flight. Each symbol is associated with a shadow which is drawn with an appropriate shape and orientation. The location of the shadow indicates the position of the aircraft on the earth's surface and the distance between the shadow and the aircraft indicates altitude. The shadow also aids in determining whether an aircraft is moving toward or away from the viewer. A vector which projects from each shadow allows coarse judgments of speed and heading.

Additional features that may be incorporated in perspective displays to improve the interpretability of the surrounding environment are illustrated in a display that has been developed by the Mission Systems Research Centre,

Defence Science and Technology Organisation. The display models radar beams associated with targets in the environment in three dimensions; this feature could support effective navigation to avoid detection by enemy radar. Another feature of the display is the depiction of threat domes as a 3D region which could improve operators' ability to monitor incursions into these zones.

10. Conclusion

This report has highlighted several human factors considerations that must be taken into account before perspective displays may be safely operationalised. An important observation that was common to several of the areas that were discussed is the influence of the nature of the task on the outcome of the research findings. For instance, it was shown that perspective displays support better performance on integration tasks whereas plan-view displays support better performance on focussed-attention tasks. The effect of monocular cues in conveying an accurate perception of depth, and the effect of frame of reference and geometric parameters on performance was also task dependent. This observation emphasises the importance of having comprehensive knowledge about the characteristics of the tasks for which the perspective display is being considered and the importance of evaluating perspective displays in the appropriate context with experienced operators prior to operationalisation.

Studies which have demonstrated performance advantages associated with perspective displays, compared to conventional 2D displays, provide a motivation for continuing the research and development of this type of technology. Particular effort should be directing towards understanding the distorting effects of representing perspective information on a 2D surface. Visual enhancement techniques which may improve the interpretability of perspective displays should also be investigated. More work should also be done on the effects of giving operators the flexibility to switch between alternate display formats, for example, an egocentric and exocentric frame of reference.

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19. ABSTRACT Three-dimensional displays may be a more effective way of presenting spatial information to operators than conventional two-dimensional displays because all three dimensions of space may be represented in a spatial format. Of several three-dimensional computer graphics systems that are currently available, perspective displays may be the most viable option for implementation at the present time. Previous research shows that perspective displays support better performance than plan-view displays on navigation, spatial awareness, and integration tasks. However, several issues need to be carefully considered and understood before perspective displays may be safely operationalised. This report reviews these issues; monocular cues for depth perception, multiple cue interaction, frame of reference, perspective geometry, and geometric and symbolic enhancement features.							